Geology

Evidence for mechanically coupled lithosphere in central Asia and resulting implications

Chun-Yong Wang, Lucy M. Flesch, Paul G. Silver, Li-Jun Chang and Winston W. Chan

Geology 2008;36;363-366
doi: 10.1130/G24450A.1

Notes

Evidence for mechanically coupled lithosphere in central Asia and resulting implications

Chun-Yong Wang Institute of Geophysics, China Earthquake Administration, Beijing 100081, People's Republic of China
Lucy M. Flesch Department of Earth & Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907, USA
Paul G. Silver Carnegie Institution of Washington, Washington, DC 20015, USA
Li-Jun Chang Institute of Geophysics, China Earthquake Administration, Beijing 100081, People's Republic of China
Winston W. Chan Multimax Corporation, 1441 McCormick Drive, Landover, Maryland 20774, USA

ABSTRACT

The recent dramatic increase in seismic anisotropy and surface global positioning system (GPS) data for central Asia permits a comprehensive examination of the mantle's role in mountain building. A joint analysis of 178 shear-wave-splitting and ~2000 GPS observations using a new technique reveals that the crust and lithospheric mantle deform coherently, arguing for crust-mantle mechanical coupling during deformation. The observed spatial variations in anisotropy reflect the large-scale pattern of lithospheric deformation, as well as a change in deformational style from simple shear on the Tibetan Plateau transitioning to pure shear in surrounding regions.

Keywords: anisotropy, lithospheric deformation, global positioning system, central Asia.

INTRODUCTION

How mountains form is one of Earth science's basic questions. Progress has been made in understanding crustal properties of continental lithosphere in the mountain-building process, i.e., the anomalous thickness and high topography created by the process of continent-continent collision. The role of the lithospheric mantle in orogeny, however, is less clear, as reflected in the range of mantle properties found in current models for orogenic deformation (England and Houseman, 1986, 1989; Royden et al., 1997; Tapponnier et al., 1982; Thatcher, 2006; Meade, 2007). If the lithospheric mantle deformation could be measured directly and compared to the surface, it would constitute an important means of assessing the mantle's role in orogens. Such a means is now available through the joint analysis of surface deformation data and mantle seismic anisotropy (Flesch et al., 2005). A recent increase in the number of both types of data in central Asia and conceptual advances in their joint analysis provide strong support for mechanically coupled orogenic lithosphere throughout this region.

GEOPHYSICAL DATA

Mantle anisotropy is constrained with 178 SKS shear-wave splitting observations, 73 from previously published studies (McNamara et al., 1994; Huang et al., 2000; Flesch et al., 2005; Lev et al., 2006; Sol et al., 2007) and 105 new ones analyzed in this study obtained from portable deployments in Yunnan (2002) (Chang et al., 2006), eastern Tibet and Sichuan (2004–2006, Chinese Earthquake Administration, Carnegie Institution of Washington, Saint Louis University, Multimax Corporation), and permanent stations from Chinese regional and national networks (Zhao et al., 1997) (Fig. 1; GSA Data Repository Table DR1[1]). We have used standard methods (Silver and Chan, 1991; Wolfe and Silver, 1998) to calculate individual splitting observations of the fast polarization direction, ϕ, and delay time, δt, as well as station stacks. For our own observations, only those stations where splitting could unambiguously be detected were used. We proceed assuming that the seismic anisotropy arises from a single homogenous mantle layer because: (1) we checked our data for evidence of two anisotropic layers by the analysis of back-azimuthal variations in both ϕ and δt (Silver and Savage, 1994), but found none (Figs. DR1–DR3; see footnote 1), and (2) several studies have concluded that the crust cannot account for SKS splitting observations in central Asia based on studies of crustal splitting (McNamara et al., 1994; Herquel et al., 1995; Sherrington et al., 2004; Frederiksen et al., 2003; Ozacar and Zandt, 2004; Karalliyadda et al., 2007).

For the surface deformation field, we have used ~2000 global positioning system (GPS) observations (Abdrakhmatov et al., 1996; Bendick

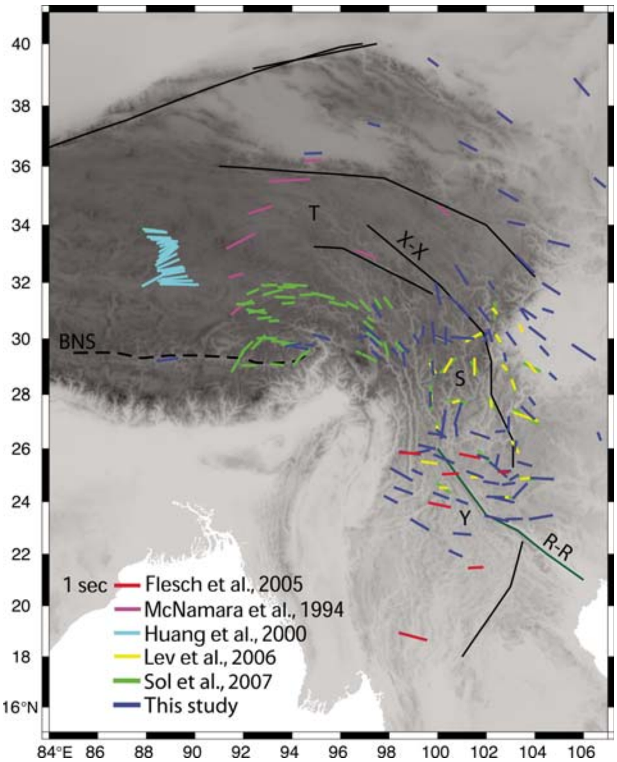

Figure 1. Shear wave splitting data set used in this study. See also Table DR1 (see footnote 1). Orientation of lines gives fast polarization direction, ϕ, and delay time, δt, given by length of bar, according to legend. These represent several previous portable deployments, one recent deployment, as well as the analysis of permanent stations from a variety of networks. Black lines represent large left-lateral faults, and green lines represent right-lateral faults. Plot is shown in degrees east and north. (X-X—Xianshuihe-Xiaojiang fault, R-R—Red River fault, T—Tibet, S—Szechwan, Y—Yunnan, BNS—Bangong-Nujiang suture).

[1]GSA Data Repository item 2008091, method equations, uncertainty descriptions, Figures DR1–DR6, and Tables DR1–DR2, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

et al., 2000; Calais et al., 1998; Chen et al., 2000; Heki et al., 1999; Michel et al., 2001; Shen et al., 2000, 2001; Simons et al., 1999; Wang et al., 2001; Yu et al., 1999; Zhang et al., 2004; Zhu et al., 2000; http://sideshow.jpl.nasa.gov/mbh/series.html) and Quaternary fault slip rates (England and Molnar, 1997) to quantify the velocity, V_c, velocity gradient tensor, $\mathbf{L}_c$, and strain-rate tensor, $\dot{\boldsymbol{\varepsilon}}_c$, following the method of Haines and Holt (1993) and Haines et al. (1998) (Fig. DR4).

JOINT ANALYSIS OF SHEAR-WAVE SPLITTING AND GPS DATA

We directly compare mantle anisotropy with predicted fast polarization directions, ϕ_c, from the surface deformation field. We assume A-type lattice preferred orientation (LPO) in olivine, where the olivine *a*-axis is parallel to the finite-strain maximum shear direction for simple shear (Zhang and Karato, 1995), and the finite-strain extension direction for pure shear (Nicolas et al., 1973). For the nearly vertically propagating shear waves we are using, and assuming that the *a*-axis concentration is subhorizontal, ϕ_c will have the same orientation as the *a*-axis concentration. While other LPO types have been proposed for elevated stress and water content (Jung and Karato, 2001), the most successful LPO type for modeling mantle anisotropy (Davis et al., 1997; Holt, 2000; Silver and Holt, 2002; Flesch et al., 2005), and the most prevalent type found in natural mantle samples (Silver et al., 1999; Mainprice et al., 2000; Ben-Ismaïl et al., 2001), is A-type.

To predict the mantle finite-strain field $\boldsymbol{\varepsilon}_m$ that determines the LPO from the surface instantaneous quantities $\mathbf{L}_c$ and $\dot{\boldsymbol{\varepsilon}}_c$, we assume that $\boldsymbol{\varepsilon}_m$ is formed by the integration of $\dot{\boldsymbol{\varepsilon}}_c$, over time (Kaminski and Ribe, 2002). This correspondence is straightforward under the idealized conditions of both simple and pure shear because the instantaneous and finite-strain maximum-shear and maximum-extension directions are invariant under simple shear and pure shear, respectively. Therefore, ϕ_c will be parallel to the surface-strain instantaneous maximum-shear and/or maximum-extension direction in a simple-shear and/or pure shear-regime. Knowledge of the continuous strain-rate field, $\dot{\boldsymbol{\varepsilon}}_c$, thus allows the prediction of ϕ_{ssl}, ϕ_{ssr}, and ϕ_{ps} for left-lateral simple shear, right-lateral simple shear, and pure shear, respectively, at each splitting observation. In principle, we can use $\mathbf{L}_c$ to determine which of these three is the correct direction by calculating the kinematic vorticity number W_k (McKenzie, 1979; Means, 1990; Fossen and Tikoff, 1993) (see the Data Repository), which is a ratio of rotation to shear. Thus, W_k is ±1 for left- and/or right-lateral simple shear and $W_k = 0$ for pure shear (Kaminski and Ribe, 2002). Values of $W_k = 0.5$ tend to result in simple shear (McKenzie, 1979). If there is external rigid-body rotation unrelated to the internal deformation generating the anisotropy, W_k will not reflect the style of internal deformation. We therefore estimate the amount of external rotation using the line rotation method (Lamb, 1987; Holt and Haines, 1993), assuming that the observed splitting orientation constitutes a deformational invariant direction (i.e., is not rotated by the internal deformation). The calculated external rotation is then removed from $\mathbf{L}_c$ to calculate a corrected W_k^*, which is then used to choose ϕ_c (Table DR2; see footnote 1).

We compared data in central and northern Tibet (above the Bangong-Nujiang suture) and surrounding off-plateau regions. Observations south of the Bangong-Nujiang suture are plotted but not compared because of the likely influence of Indian lithosphere (e.g., Kosarev et al., 1999). The pattern of splitting fast polarization directions exhibits several basic features (Figs.1 and 2). There is an overall west-to-east rotation of ϕ from NE-SW to EW, to NW-SE, to N-S. The N-S trend then abruptly rotates to E-W below ~27ºN (Lev et al., 2006; Sol et al., 2007). Comparing splitting observations and predictions based on W_k^* reveals a close correspondence. Over most of the Tibetan plateau, ϕ is well predicted by $\phi_c = \phi_{ssl}$ (Flesch et al., 2005). Along the boundaries of the plateau to the southeast, northeast, and surrounding regions, it

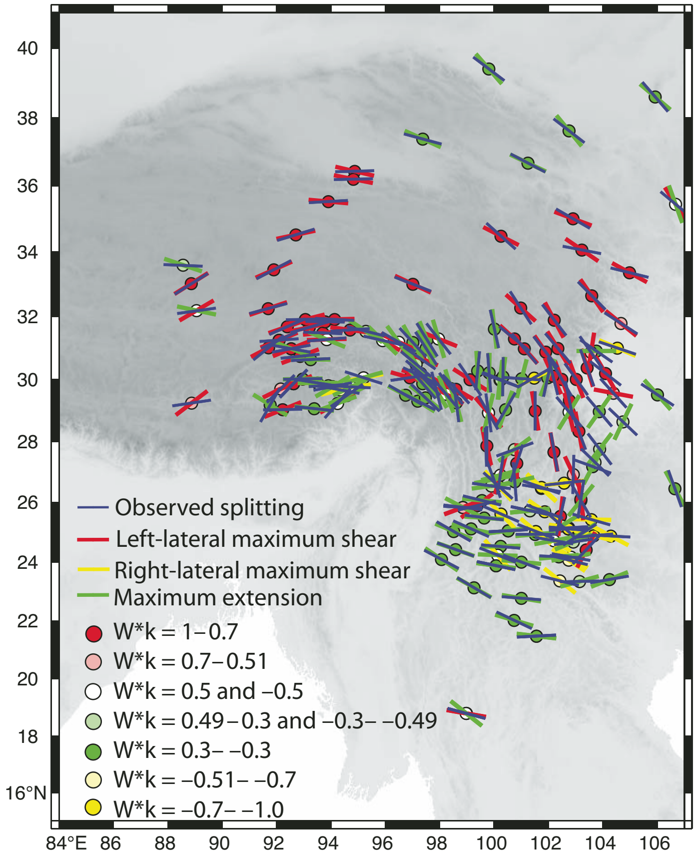

Figure 2. Comparison between predicted anisotropy direction from the surface deformation field ϕ_c, and splitting observations ϕ (observations of Huang et al. [2000] have been spatially averaged). For each observation point, we use $\phi_c = \phi_{ssl}$ (left-lateral simple shear, red), $\phi_c = \phi_{ssr}$ (right-lateral simple shear, yellow), or $\phi_c = \phi_{ps}$ (maximum extension pure shear, green) depending on value of kinematic vorticity number, W_k^* (see legend). For $W_k^* = \pm 0.5$, both pure shear and simple shear orientations are shown. Note the strong correlation between the predictions and data, as well as the systematic change in deformational style from left-lateral simple shear on the plateau to pure shear at the plateau boundaries and surrounding regions. Figure DR6 (see footnote 1) shows W_k^* plotted alone. Plot is shown in degrees east and north.

is $\phi_c = \phi_{ps}$ that successfully predicts ϕ, including the change in splitting orientation at 27ºN and the more subtle west to east, WNW-ESE to ENE-WSW rotation in ϕ south of 27ºN. The zone between 28ºN and 30ºN appears to represent a more complex transition between left-lateral simple shear and pure shear styles of deformation. Thus there appear to be two transitions: (1) from simple shear on the Tibetan plateau to pure shear along the boundaries and surrounding regions, and (2) within the pure shear regime a change from north-south to east-west splitting and extension directions (Fig. DR4). Splitting observations close to the Xianshuihe-Xiaojiang fault system are parallel to the fault and produce W_k^* ~1, indicating that this well-developed left-lateral fault has a strong local influence through Tibet, Szechwan, and Yunnan. Likewise, splitting observations to the east of the right-lateral Red River fault produce a W_k^* ~−1. Throughout the study area there is a correlation between the predicted ϕ_c and ϕ with an average misfit of 16.7°, indicating that deformation in the lithosphere is undergoing vertically coherent deformation (Silver, 1996). Of the 178 splitting observations, there are 14 outliers with misfits larger than 70°. Examination of these stations suggests that there are additional complexities present that are not adequately being taken into account (see the Data Repository). Exclusion of these outliers reduces the misfit to 11.8°, further strengthening the argument for vertically coherent deformation.

The previously limited splitting data, while consistent with vertically coherent deformation in Tibet (Silver, 1996; Davis et al., 1997; Flesch et al., 2005), was thought to reflect a transition to crust-mantle decoupling in Yunnan (Flesch et al., 2005; Lev et al., 2006; Sol et al., 2007). The increase in splitting observations strengthens the case for vertically coherent deformation in Tibet, and argues for this same property within the surrounding regions. A hybrid model (coupling in Tibet, decoupling in Yunnan; Flesch et al., 2005) simply cannot account for the abrupt spatial transition in splitting observations between 28°N and 26°N from N-S to E-W, and produces an overall misfit of 27.4°. This transition is also observed in the extension axes of the surface strain-rate field, as well as in the orientation of the T-axes of regional crustal seismicity (Wu et al., 2004; Figs. DR4b and DR5), demonstrating that it is both a crustal and mantle feature, consistent with vertically coherent deformation**.** This transition is expected in areas of large gravitational potential energy variations, reflecting the change from topographic gradient–parallel extension at high elevations to topographic gradient–parallel shortening at lower elevations as the collapsing lithosphere encounters resistance from the surrounding medium (Flesch et al., 2001; Lev et al., 2006).

DISCUSSION AND CONCLUSIONS

The observed vertically coherent deformation permits us to infer that the crust and lithospheric mantle are mechanically coupled. This is because deviatoric stresses associated with gravitational potential energy variations constitute half of the stress driving deformation in central Asia (collisional boundary conditions provide the other half) (Flesch et al., 2001). Because gravitational potential energy variations reside almost solely in the crust, vertically coherent deformation requires that the resulting vertical normal stresses be transmitted into the mantle by crust-mantle mechanical coupling. Attempts to model the observed mantle anisotropy with boundary conditions alone have been unsuccessful (Flesch et al., 2005).

This result forms an observational foundation with which to assess the mantle's role in the orogenic process. For example, block models (Tapponnier et al., 1982; Thatcher, 2006; Meade, 2007) produce highly localized shear along block boundaries and broad mantle deformation beneath the blocks. Because only the latter will generate mantle anisotropy, these models are mechanically equivalent to simple asthenospheric flow (Silver, 1996) for blocks that extend into the mantle (Lave et al., 1996), and may be assessed by solving for a best-fitting subasthenospheric mantle velocity (Silver and Holt, 2002; Flesch et al., 2005). Such a model produces a larger misfit, 27.3°, than vertically coherent deformation. Thus, these "blocks" are more likely upper crustal manifestations of distributed lithospheric deformation at depth (England and Molnar, 1990).

Channelized flow in a lower crustal low-viscosity (several orders of magnitude) channel (Royden et al., 1997) decouples the crust and mantle, prohibits the transmission of vertical stresses into the mantle, and does not generate vertically coherent deformation. To maintain vertically coherent deformation, this viscosity contrast must be less than one order of magnitude and will not channelize flow (Bendick and Flesch, 2007). The convective-instability hypothesis (England and Houseman, 1989; Molnar et al., 1998) predicts the presence of an asthenospheric flow field induced by lithospheric removal. This flow, however, is unlikely to look like vertically coherent deformation.

A joint analysis of SKS splitting and surface deformation data in central Asia argues for crust and lithospheric mantle that deform coherently and are mechanically coupled, implying that the orogenic mantle survives the mountain-building process. This simple style of lithospheric deformation provides a fundamental constraint for future orogenic models.

ACKNOWLEDGMENTS

We thank P. Burkett and W. Jiao for valuable assistance in the seismic field deployments. This manuscript benefited from discussions with M. Behn, W. Holt, D. Weeraratne, B. Savage, W. Thatcher, and the Friends of Tibet discussion group. We thank Einat Lev, Noah Fay, and two anonymous reviewers for thoughtful reviews. This research was conducted under support from the Continental Dynamics Program of the State Natural Scientific Foundation of China (grant 40334041) and the International Cooperation Program of the Ministry of Science and Technology of China (grant 2003DF000011), Multimax Corporation, National Science Foundation grant EAR-0215616 (Silver), and the Carnegie Institution of Washington.

REFERENCES CITED

Abdrakhmatov, K.Y., Aldazhanov, S.A., Hager, B.H., Hamburger, M.W., Herring, T.A., Kalabaev, K.B., Makarov, V.I., Molnar, P., Panasyuk, S.V., Prilepin, M.T., Reilinger, R.E., Sadybakasov, I.S., Souter, B.J., Trapeznikov, Y.A.., Tsurkov, V.Y., and Zubovich, A.V., 1996, Relatively recent construction of the Tien Shan inferred from GPS measurements of present-day crustal deformation rates: Nature, v. 384, p. 450–453, doi: 10.1038/384450a0.

Bendick, R., and Flesch, L.M., 2007, Reconciling lithospheric deformation and lower crustal flow beneath central Tibet: Geology, v. 35, p. 895–898.

Bendick, R., Bilham, R., Freymueller, J., Larson, K., and Yin, G.H., 2000, Geodetic evidence for a low slip rate in the Altyn Tagh fault system: Nature, v. 404, p. 69–72, doi: 10.1038/35003555.

Ben-Ismaïl, W., Barruol, G., and Mainprice, D., 2001, The Kaapvaal craton seismic anisotropy: A petrophysical analysis of upper mantle kimberlite nodules: Geophysical Research Letters, v. 28, p. 2497–2500, doi: 10.1029/2000GL012419.

Calais, E., Lesne, O., Deverchere, J., San'kov, V., Lukhnev, A., Miroshnitchenko, A., Buddo, V., Levi, K., Zalutzky, V., and Bashkuev, Y., 1998, Crustal deformation in the Baikal rift from GPS measurements: Geophysical Research Letters, v. 25, p. 4003–4006, doi: 10.1029/1998GL900067.

Chang, L.-J., Wang, C.-Y., and Ding, Z.-F., 2006, A study on SKS splitting beneath the Yunnan region: Chinese Journal of Geophysics, v. 49, p. 167–175.

Chen, Z., Burchfiel, B.C., Liu, Y., King, R.W., Royden, L.H., Tang, W., Wang, E., Zhao, J., and Zhang, X., 2000, Global positioning system measurements from eastern Tibet and their implications for India/Eurasia intercontinental deformation: Journal of Geophysical Research, v. 105, p. 16,215–16,227, doi: 10.1029/2000JB900092.

Davis, P., England, P., and Houseman, G.A., 1997, Comparison of shear wave splitting and finite strain from the India-Asia collision zone: Journal of Geophysical Research, v. 102, p. 27,511–27,522, doi: 10.1029/97JB02378.

England, P.C., and Houseman, G.A., 1986, Finite strain calculations of continental deformation; 2, Comparison with the India-Asia collision zone: Journal of Geophysical Research, v. 91, p. 3664–3676.

England, P., and Houseman, G.A., 1989, Extension during continental convergence, with application to the Tibetan Plateau: Journal of Geophysical Research, v. 94, p. 17,561–17,579.

England, P.C., and Molnar, P., 1990, Right-lateral shear and rotation as the explanation for strike-slip faulting in eastern Tibet: Nature, v. 344, p. 140–142, doi: 10.1038/344140a0.

England, P., and Molnar, P., 1997, The field of crustal velocity in Asia calculated from Quaternary rates of slip on faults: Geophysical Journal International, v. 130, p. 551–582, doi: 10.1111/j.1365–246X.1997.tb01853.x.

Flesch, L.M., Haines, A.J., and Holt, W.E., 2001, Dynamics of the India-Eurasia collision zone: Journal of Geophysical Research, v. 106, p. 16,435–16,460, doi: 10.1029/2001JB000208.

Flesch, L.M., Holt, W.E., Silver, P.G., Stephenson, M., Wang, C.-Y., and Chan, W.W., 2005, Constraining the extent of crust-mantle coupling in Central Asia using GPS, geologic, and shear-wave splitting data: Earth and Planetary Science Letters, v. 238, p. 248–268, doi: 10.1016/j.epsl.2005.06.023.

Fossen, H., and Tikoff, B., 1993, The deformation matrix for simultaneous simple shearing, pure shearing, and volume changes, and its application to transpression/transtension tectonics: Journal of Structural Geology, v. 15, p. 413–422, doi: 10.1016/0191–8141(93)90137-Y.

Frederiksen, A.W., Folsom, H., and Zandt, G., 2003, Neighbourhood inversion of teleseismic Ps conversions for anisotropy and layer dip: Geophysical Journal International, v. 155, p. 200–212, doi: 10.1046/j.1365–246X.2003.02043.x.

Haines, A.J., and Holt, W.E., 1993, Procedure for obtaining the complete horizontal motions within zones of distributed deformation from the inversion of strain-rate data: Journal of Geophysical Research, v. 98, p. 12,057–12,082.

Haines, A.J., Jackson, J.A., Holt, W.E., and Agnew, D.C., 1998, Representing distributed deformation by continuous velocity fields: Wellington, New Zealand, Institute of Geological and Nuclear Sciences Science Reporter, v. 98, no. 5, p. 1–121.

Heki, K., Miyazaki, S., Takahashi, H., Kasahara, M., Kimata, F., Miura, S., Vasilenko, N.F., Ivashchenko, A., and An, K.D., 1999, The Amurian Plate motion and current plate kinematics in eastern Asia: Journal of Geophysical Research, v. 104, p. 29,147–29,155, doi: 10.1029/1999JB900295.

Herquel, G., Wittlinger, G., and Guilbert, J., 1995, Anisotropy and crustal thickness of northern Tibet. New constraints for tectonic modeling: Geophysical Research Letters, v. 22, p. 1925–1928, doi: 10.1029/95GL01789.

Holt, W.E., 2000, Correlated crust and mantle strain fields in Tibet: Geology, v. 28, p. 67–70, doi: 10.1130/0091–7613(2000)28<67:CCAMSF>2.0.CO;2.

Holt, W.E., and Haines, A.J., 1993, Velocity fields in deforming Asia from the inversion of earthquake-released strains: Tectonics, v. 12, p. 1–20.

Huang, W.-C., Ni, J., Tilmann, F., Nelson, D., Guo, J., Zhao, W., Mechie, J., Kind, R., Saul, J., Rapine, R., and Hearn, T., 2000, Seismic polarization anisotropy beneath the central Tibetan Plateau: Journal of Geophysical Research, v. 105, p. 27,979–27,989, doi: 10.1029/2000JB900339.

Jung, H., and Karato, S.I., 2001, Water-induced fabric transitions in olivine: Science, v. 293, p. 1460–1463, doi: 10.1126/science.1062235.

Kaminski, E., and Ribe, N.L.M., 2002, Timescales for the evolution of seismic anisotropy in mantle flow: Geochemistry, Geophysics, Geosystems, v. 3, doi: 10.1029/2001GC000222.

Karalliyadda, S., Weeraratne, D., and Silver, P.G., 2007, Evidence for vertical coherent deformation in eastern Tibet from splitting of crustal S phases: Eos (Transactions, American Geophysical Union), v. 88, Fall Meeting Supplemenet, Abstract T31B-0463.

Kosarev, G., Kind, R., Sobolev, S.V., Yuan, X., Hanka, W., and Oreshin, S., 1999, Seismic evidence for a detached Indian lithospheric mantle beneath Tibet: Science, v. 283, p. 1306–1309, doi: 10.1126/science.283.5406.1306.

Lamb, S.H., 1987, A model for tectonic rotations about a vertical axis: Earth and Planetary Science Letters, v. 84, p. 75–86, doi: 10.1016/0012–821X(87)90178–6.

Lave, J., Avouac, J.P., Lacassin, R., Tapponnier, P., and Montagner, J.P., 1996, Seismic anisotropy beneath Tibet; evidence for eastward extrusion of the Tibetan lithosphere?: Earth and Planetary Science Letters, v. 140, p. 83–96, doi: 10.1016/0012–821X(96)00045–3.

Lev, E., Long, M.D., and van der Hilst, R.D., 2006, Seismic anisotropy in eastern Tibet from shear wave splitting reveals changes in lithospheric deformation: Earth and Planetary Science Letters, v. 251, p. 293–304, doi: 10.1016/j.epsl.2006.09.018.

Mainprice, D., Barruol, G., and Ben Ismaìl, W., 2000, The anisotropy of the Earth's mantle: From single crystal to polycrystal, *in* Karato, S., et al., eds., Mineral physics and seismic tomography: From atomic to global: American Geophysical Union Geophysical Monograph 117, p. 237–264.

McKenzie, D., 1979, Finite deformation during fluid flow: Royal Astronomical Society Geophysical Journal, v. 58, p. 689–715.

McNamara, D.E., Owens, T.J., Silver, P.G., and Wu, F.T., 1994, Shear wave anisotropy beneath the Tibetan Plateau: Journal of Geophysical Research, v. 99, p. 13,655–13,665, doi: 10.1029/93JB03406.

Meade, B.J., 2007, Present-day kinematics at the India-Asia collision zone: Geology, v. 35, p. 81–84, doi: 10.1130/G22924A.1.

Means, W.D., 1990, Kinematics, stress, deformation and material behaviour: Journal of Structural Geology, v. 12, p. 953–971, doi: 10.1016/0191–8141(90)90092-D.

Michel, G.W., Yu, Y.Q., Zhu, S.Y., Reigber, C., Becker, M., Reinhard, E., Simons, W., Ambrosius, B., Vigny, C., Chamot-Rooke, N., Le Pichon, X., Morgan, P., and Matheussen, S., 2001, Crustal motion and block behaviour in SE-Asia from GPS measurements: Earth and Planetary Science Letters, v. 187, p. 239–244, doi: 10.1016/S0012–821X(01)00298–9.

Molnar, P., Houseman, G.A., and Conrad, C.P., 1998, Rayleigh-Taylor instability and convective thinning of mechanically thickened lithosphere: Effects of non-linear viscosity decreasing exponentially with depth and of horizontal shortening of the layer: Geophysical Journal International, v. 133, p. 568–584, doi: 10.1046/j.1365–246X.1998.00510.x.

Nicolas, A., Boudier, F., and Boullier, A.M., 1973, Mechanisms of flow in naturally and experimentally deformed peridotites: American Journal of Science, v. 273, p. 853–876.

Ozacar, A.A., and Zandt, G., 2004, Crustal seismic anisotropy in central Tibet: Implications for deformational style and flow in the crust: Geophysical Research Letters, v. 31, L23601, doi: 10.1029/2004GL021096.

Royden, L.H., Burchfiel, B.C., King, R.W., Wang, E., Chen, Z., Shen, F., and Liu, Y., 1997, Surface deformation and lower crustal flow in eastern Tibet: Science, v. 276, p. 788–790.

Shen, Z.K., Zhao, C.K., Yin, A., Li, Y.X., Jackson, D.D., Fang, P., and Dong, D.N., 2000, Contemporary crustal deformation in east Asia constrained by global positioning system measurements: Journal of Geophysical Research, v. 105, p. 5721–5734, doi: 10.1029/1999JB900391.

Shen, Z.K., Wang, M., Li, X.Y., Jackson, D.D., Yin, A., Dong, D.N., and Fang, P., 2001, Crustal deformation along the Altyn Tagh fault system, western China, from GPS: Journal of Geophysical Research, v. 106, p. 30,607–30,621, doi: 10.1029/2001JB000349.

Sherrington, H.F., Zandt, G., and Fredriksen, A., 2004, Crustal fabric in the Tibetan Plateau based on wave form inversions: Journal of Geophysical Research, v. 109, B02312, doi: 10.1029/2002JB002345.

Silver, P.G., 1996, Seismic anisotropy beneath the continents: Probing the depths of geology: Annual Review of Earth and Planetary Sciences, v. 24, p. 385–432, doi: 10.1146/annurev.earth.24.1.385.

Silver, P.G., and Chan, W.W., 1991, Shear-wave splitting and subcontinental mantle deformation: Journal of Geophysical Research, v. 96, p. 16,429–16,454.

Silver, P.G., and Holt, W.E., 2002, The mantle flow field beneath western North America: Science, v. 295, p. 1054–1057, doi: 10.1126/science.1066878.

Silver, P.G., and Savage, M., 1994, The interpretation of shear-wave splitting parameters in the presence of two anisotropic layers: Geophysical Journal International, v. 119, p. 949–963, doi: 10.1111/j.1365–246X.1994.tb04027.x.

Silver, P.G., Mainprice, D., Ismail, W.B., Tommasi, A., and Barruol, G., 1999, Mantle structural geology from seismic anisotropy, *in* Fei, Y., et al., eds., Mantle petrology: Field observations and high pressure experimentation: A tribute to Francis R. (Joe) Boyd: Chemical Society [London] Special Publication 6, p. 79–103.

Simons, W.J.F., Ambrosius, B.A.C., Noomen, R., Angermann, D., Wilson, P., Becker, M., Reinhart, E., Walpersdorf, A., and Vigny, C., 1999, Observing plate motions in SE Asia: Geodetic results of the GEODYSSEA project: Geophysical Research Letters, v. 26, p. 2081–2084, doi: 10.1029/1999GL900395.

Sol, S., Meltzer, A., Burgmann, R., van der Hilst, R.D., King, R., Chen, Z., Koons, P.O., Lev, E., Liu, Y.P., Zeitler, P.K., Zhang, X., Zhang, J., and Zurek, B., 2007, Geodynamics of the southeastern Tibetan Plateau from seismic anisotropy and geodesy: Geology, v. 35, p. 563–566, doi: 10.1130/G23408A.1.

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., and Cobbold, P., 1982, Propagating extrusion tectonics in Asia; new insights from simple experiments with plasticine: Geology, v. 10, p. 611–616, doi: 10.1130/0091–7613(1982)10<611:PETIAN>2.0.CO;2.

Thatcher, W., 2006, Microplate model for the present-day deformation of Tibet: Journal of Geophysical Research, v. 111, doi: 10.1029/2005JB004244.

Wang, Q., Zhang, P.Z., Niu, Z.J., Freymueller, J.T., Lai, X., Li, Y.X., Zhu, W.Y., Liu, J.N., Bilham, R., and Larson, K.M., 2001, Present-day crustal deformation in China constrained by global positioning system measurements: Science, v. 294, p. 574–577, doi: 10.1126/science.1063647.

Wolfe, C.J., and Silver, P.G., 1998, Seismic anisotropy of oceanic upper mantle: Shear-wave splitting observations and methodologies: Journal of Geophysical Research, v. 103, p. 749–771, doi: 10.1029/97JB02023.

Wu, J.-P., Ming, Y.-H., and Wang, C.-Y., 2004, Source mechanism of small-moderate earthquakes and tectonic stress field in Yunnan Province: Acta Seismologica Sinica, v. 17, p. 509–517, doi: 10.1007/s11589–004–0032–2.

Yu, S.B., Kuo, L.C., Punongbayan, R.S., and Ramos, E.G., 1999, GPS observation of crustal deformation in the Taiwan-Luzon region: Geophysical Research Letters, v. 26, p. 923–926, doi: 10.1029/1999GL900148.

Zhang, P.Z., Shen, Z., Wang, M., Gan, W.J., Burgmann, R., and Molnar, P., 2004, Continuous deformation of the Tibetan Plateau from global positioning system data: Geology, v. 32, p. 809–812, doi: 10.1130/G20554.1.

Zhang, S., and Karato, S.I., 1995, Lattice preferred orientation of olivine aggregates deformed in simple shear: Nature, v. 375, p. 774–777, doi: 10.1038/375774a0.

Zhao, K., Zhuang, C.T., and Shen, S.J., 1997, A feedback broadband seismometer applying to digital seismograph network: Earthquake, v. 17, supplement, p. 36–44.

Zhu, W.Y., Wang, X.Y., Cheng, Z.Y., Xiong, Y.Q., Zhang, Q., Ye, S.H., Ma, Z.J., Chen, J.Y., Xu, H.Z., Wei, Z.Q., Lai, X., Liu, J.N., Jin, B.R., Ren, J.W., and Wang, Q., 2000, Crustal motion of Chinese mainland monitored by GPS: Science in China, ser. D—Earth Science, v. 43, p. 394–400.

Manuscript received 4 October 2007
Revised manuscript received 16 January 2008
Manuscript accepted 19 January 2008

Printed in USA